CONTROLLING CRACK WIDTHS IN WALLS RESTRAINED AT THEIR BASE AND ENDS

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ABSTRACT

Following casting, concrete cracks if early-age thermal (EAT) and long-term (LT) shrinkage movement is restrained. Crack control is of particular importance in walls which rely solely on concrete for water tightness, such as retaining walls and water resisting tanks. It is well established that the cracking behaviour of end restrained members is very different from that of edge restrained walls. For this reason, both restraint types are considered separately in literature and in codes of practice such as Eurocode 2 (EN 1992). In reality, combined edge and end restraint is present in many reinforced concrete (RC) structures. In the absence of design recommendations for combined restraint, U.K. engineers commonly design crack control reinforcement for end restraint as it is the worst case. In the authors' opinion, this is wasteful as it leads to the provision of unnecessary reinforcement. To this end, an experimental programme was conducted to investigate cracking in RC walls with combined base and end restraint. The measured and calculated crack widths are compared with the predictions of EN 1992 for edge and end restraint. The results suggest that crack widths in walls with combined edge and end restraint can be calculated with the EN 1992 equations for cracking in edge restrained walls.

Keywords: crack width, crack control, early-age thermal, edge and end restraint, shrinkage.

Nomenclature

c	-	cover to longitudinal reinforcement
k_1	-	coefficient taking into account bond properties of reinforcement
k_2	-	strain distribution coefficient
k_3, k_4	-	coefficients
k_c	-	coefficient taking account of stress distribution within the section
$s_{r,max}$	-	maximum final crack spacing (with 5 % probability of being exceeded)
w_k	-	maximum crack width (with 5 % probability of being exceeded)
A_{ct}	-	area of concrete in tensile zone
A_s	-	area of tension reinforcement
$A_{c,eff}$	-	area of concrete in tension surrounding reinforcement
C_1	-	constant related to the shape of the bond stress distribution
C_2, C_3, C_4	-	constants found experimentally
K_1	-	creep coefficient
R_1, R_2, R_3	-	restraint factors at different stages in concrete life
R_{ax}	-	external restraint factor
T_1	-	temperature fall beteen hydration peak and ambient
T_2	-	seasonal temperature variations
α_e	-	modular ratio (ratio of elastic modulus of elasticity of steel and that of concrete)
ε_{ca}	-	autogenous shrinkage strain
ε_{cd}	-	drying shrinkage strain
ε_{ctu}	-	ultimate tensile strain capacity of concrete
ε_{free}	-	free strain which would occur if the member is completely unrestrained
ε_{cm}	-	mean strain in concrete between cracks
ε_{cr}	-	crack-inducing strain i.e. proportion of restrained strain relieved when a crack occurs ($\varepsilon_{sm} - \varepsilon_{cm}$)

ε_{sm} - mean reinforcement strain

ρ - steel ratio based on area of concrete in tenison $(= A_s/A_{ct})$
$\rho_{p,eff}$ - effective reinforcement ratio $(= A_s/A_{c,eff})$
$\emptyset$ - reinforcement bar diameter

1. Introduction

Concrete structures are affected by EAT and LT shrinkage volumetric changes. If restrained from contracting, concrete invariably cracks because of its low tensile strength. One of the most common causes of damage in RC structures is excessive cracking, which can result in unacceptable visual appearance, water leakage, concrete durability impairment, reduced strength and corrosion of steel reinforcement, all of which are costly to rectify.

In practice, it is very difficult, if not impossible, to avoid external restraining newly cast in-situ concrete members. The two main types of external restraint are base (or edge) and end restraint. Examples of edge and end restraint are a RC wall cast against a stiff foundation base (see Fig. 1a) and a RC slab cast between stiff cores (see Fig. 1b).

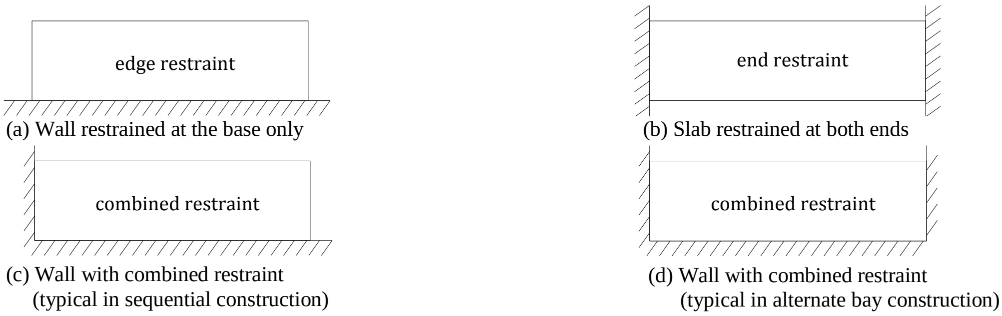


Fig. 1. Restraint types

EN 1992 (BSI, 2004, BSI, 2006) gives guidance on the calculation of crack widths for end and edge restraint but not combined edge and end restraint, which frequently occurs in practice with typical examples being walls cast against previously cast wall panels as shown in Fig. 1c and 1d. This paper investigates EAT and LT cracking in walls restrained at their base and both ends (Fig. 1d).

2. Problem definition

2.1 Literature

Previous literature shows the cracking behaviour of edge and end restrained RC elements to be very different. Cracks can form anywhere within end restrained elements because the axial load is constant along the length of the member. Consequently, cracks reduce the stiffness of the entire system and stresses reduce uniformly along the member length following the development of each successive crack. In base restrained walls, however, restraint varies along the length and height of the wall and thus, cracks only form at locations of high restraint (Al Rawi & Kheder, 1990). In end restrained members, reinforcement controls cracking by distributing the crack-inducing extension between multiple cracks along the length of the element. In the case of edge restrained walls, however, crack widths depend on the product of the restrained strain and the crack spacing, which is related to the reinforcement arrangement and wall geometry (Stoffers, 1978, Al Rawi & Kheder, 1990, Kheder et al., 1994, Kheder, 1997).

Due to these differences, researchers have studied base and end restraint separately and developed different design approaches for each (Micallef, 2015). The majority of experimental programmes have focussed on cracking in end restrained RC elements with far fewer investigations of cracking in edge restrained members (Micallef, 2015). To the authors' knowledge, no laboratory-based experimental work has been carried out on cracking in RC elements subject to combined edge and end restraint.

2.2 *Eurocode 2 (EN 1992)*

2.2.1 Walls with either edge or end restraint

BS EN 1992-3:2006 (BSI, 2006) in conjunction with BS EN 1992-1-1:2004 (BSI, 2004) (which are collectively referred to as EN 1992 in this paper) provides equations for calculating design crack widths in edge and end restrained members. EN 1992 also recommends limiting design crack widths dependent on the nature and usage of the structure. The maximum crack width, w_k is given by the product of the maximum crack spacing, $s_{r,max}$ and crack-inducing strain, $(\varepsilon_{sm} - \varepsilon_{cm})$ or ε_{cr}, as given by equation (1).

For the calculation of the maximum crack spacing using equation (2), EN 1992 combines the classical "slip" and "no-slip" approaches. Crack spacing is assumed to vary with concrete cover, c and the ratio of bar diameter to effective reinforcement ratio, $\emptyset/\rho_{p,eff}$.

$$w_k = s_{r,max}\,(\varepsilon_{sm} - \varepsilon_{cm}) \tag{1}$$

$$s_{r,max} = k_3 c + k_1 k_2 k_4 \frac{\emptyset}{\rho_{p,eff}} \tag{2}$$

EN 1992 uses different expressions to calculate the crack-inducing strain in end (3) and edge restrained walls (4). Equation (5) gives the crack-inducing strain for edge restraint according to CIRIA Report C660 (Bamforth, 2011), which is typically used in conjunction with EN 1992-3 in the U.K. Whereas the maximum crack width in end restrained members depends on the concrete strength, $f_{ct,eff}$, crack widths in edge restrained walls are calculated in terms of the restrained EAT ($R_1\alpha_c T_1$), autogenous ($R_1\varepsilon_{ca}$), LT thermal ($R_2\alpha_c T_2$) and shrinkage ($R_3\varepsilon_{cd}$) strains.

EN 1992 end restraint:

$$(\varepsilon_{sm} - \varepsilon_{cm}) = \frac{0.5\,\alpha_e\,k_c\,k\,f_{ct,eff}}{E_s}\left(1 + \frac{1}{\alpha_e \rho}\right) \tag{3}$$

EN 1992 edge restraint:

$$(\varepsilon_{sm} - \varepsilon_{cm}) = R_{ax}\,\varepsilon_{free} = \varepsilon_{cr} \tag{4}$$

CIRIA C660 edge restraint:

$$\varepsilon_{cr} = K_1\,[R_1(\alpha_c T_1 + \varepsilon_{ca}) + R_2\alpha_c T_2 + R_3\varepsilon_{cd}] - 0.5\varepsilon_{ctu} \tag{5}$$

2.2.2 Walls with combined edge and end restraint

Edge and end restraint are limiting cases with end restraint being most severe. In practice, it is very likely that a combination of edge and end restraint is present (Forth & Martin, 2014). EN 1992 does not provide guidance on the calculation of crack widths in walls with combined edge and end restraint. Consequently, some designers conservatively design for the severest of end and edge restraint when combined restraint is present.

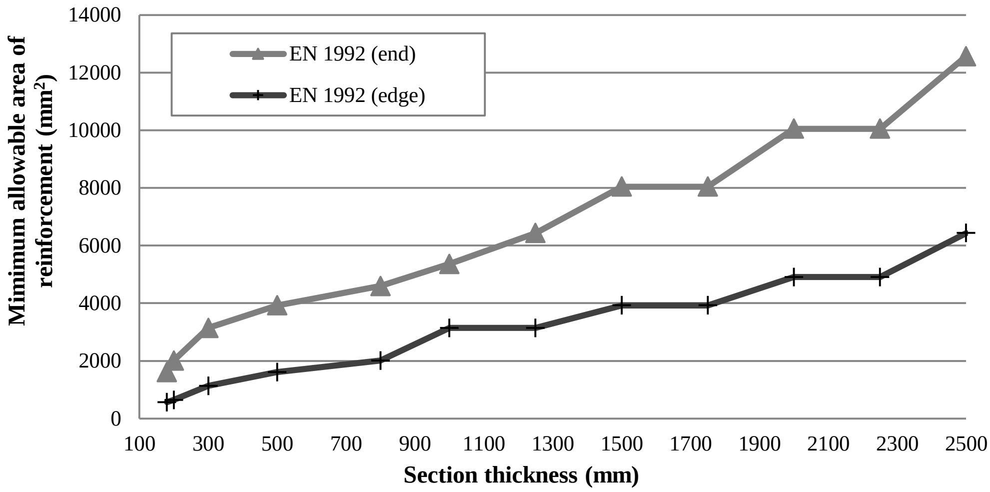


Fig. 2. Minimum reinforcement areas required to control crack widths to 0.2 mm using (3) and (5)

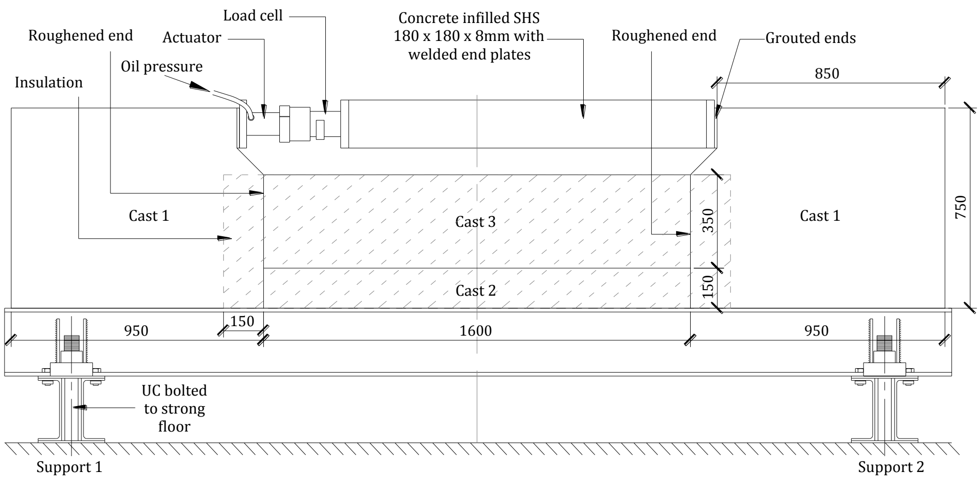
Fig. 2 shows the minimum steel reinforcement areas provided with standard U.K. reinforcement bars at 100 mm, 125 mm, 150 mm and 175 mm centres, required to control crack widths to 0.2 mm using (3) and (5), assuming a concrete grade of C30/37 and 40 mm cover to reinforcement. Fig. 2 demonstrates that an improved crack width calculation method is required for combined restraint because making the worst case assumption of end restraint massively increases the area of reinforcement required for crack control. Providing unnecessary reinforcement is undesirable as it has an adverse impact on cost, buildability and sustainability.

2.3 Research relevance

The interaction of edge and end restraint is unclear and not covered in EN 1992. To the authors' knowledge, there are no experimental data from laboratory tests on cracking in walls with combined edge and end restraint, which commonly occur in practice. Consequently, an experimental programme was developed by the authors to study EAT and LT cracking in walls with combined edge and end restraint.

3. Experimental methodology

A series of tests was carried out in the Structures Laboratory of the Department of Civil and Environmental Engineering at Imperial College London to observe EAT and LT cracking caused by imposed restraint. The aim was to develop an improved design method for crack control reinforcement in walls with combined edge and end restraint.



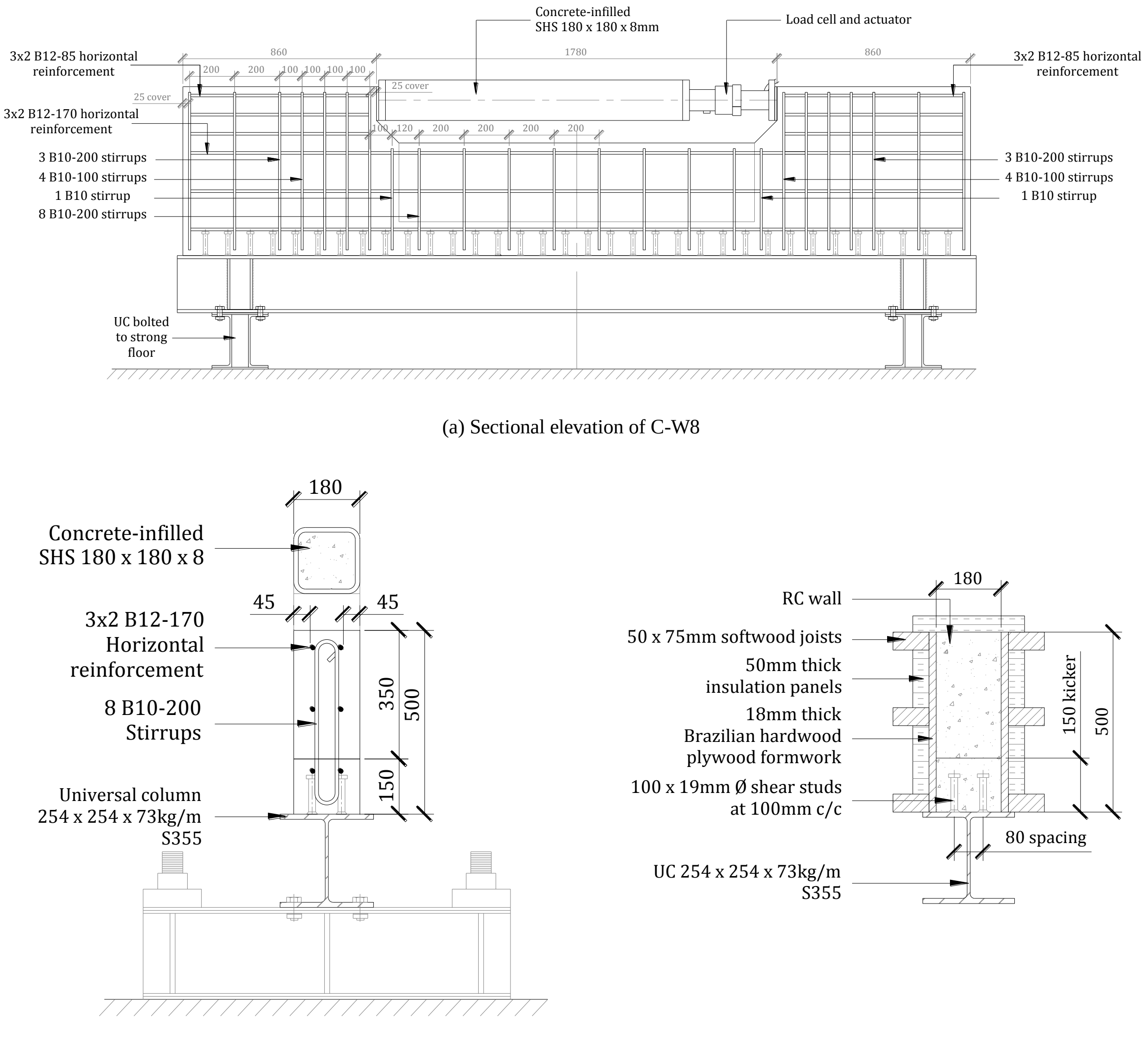
(a) General setup and casting sequence

(b) View of experimental setup

Fig. 3. Experimental setup for walls with combined edge and end restraint (all dimensions are in mm)

Fig 3. shows the typical setup for the RC specimens, including the casting sequence (Fig. 3a). Edge restraint was provided by means of a hot rolled steel universal column (UC) section (UC 254 x 254 x 73 kg/m). A steel section was chosen because, unlike concrete, steel is not subject to time-dependent effects such as creep or shrinkage. A 150 mm deep concrete kicker (cast 2) was cast onto the UC at least two weeks prior to casting the remaining wall. The reasons for casting a kicker were to simulate the boundary conditions of a wall being cast onto a concrete base as well as to minimise heat losses through the UC. In addition, the presence of the older kicker increased the base restraint further. Pairs of 100 x 19 mm shear connectors spaced at 100 mm centres were used to provide a shear key between the restraining steel beam and concrete kicker. The close spacing of the shear connectors was chosen to minimise slip between the steel UC and the kicker.

End restraint was provided by the older concrete ends (cast 1), between which the new concrete was cast. The 750 mm high ends were cast at least 2 weeks before the remainder of the wall. In addition, a concrete-infilled square hollow section (SHS) 180 x 180 x 8 mm (having similar axial stiffness to the base UC) was used at the top of the wall to maximise the efficiency of the end restraint.



(a) Sectional elevation of C-W8

(b) Cross-section details at centreline of C-W8

(c) Formwork and insulation details

Fig. 4. Typical cross-sectional reinforcement and formwork details (all dimensions are in mm)

Typical reinforcement details are shown in Fig. 4a and 4b. Fig. 4c shows the formwork details of the central part of the wall (cast 3). Table 1 summarises the characteristics of the four tests carried out on RC walls with combined edge and end restraint. The tests form part of a programme of eight tests on RC walls with either edge or combined edge and end restraint.

Table 1. Experimental wall characteristics

Wall notation	Horizontal bar diameter (mm)	Horizontal bar spacing (mm)	Concrete cover – face 1 (mm)	Concrete cover – face 2 (mm)	RC wall height (mm)
C-W5	12	100	15	25	500/750*
C-W6	12	100	45	45	500/750*
C-W7	16	200	45	45	500/750*
C-W8	12	200	45	45	500/750*

* The central wall height was 500 mm whereas ends were 250 mm higher (i.e. 750 mm)

The concrete mix design had a water-cement ratio of 0.53. A very high cement content of 500 kg/m^3 was specified in the concrete mix to achieve sufficient peak hydration temperatures to ensure EAT cracking. The concrete was insulated using 50 mm thick insulation panels with a thermal conductivity of 0.44 W/m^{2}K. After about 18 to 20 hours from casting, the insulation was removed and formwork struck.

Following casting of the wall ends (cast 1) and kicker (cast 2), the UC ends were bolted to the laboratory strong floor and all instrumentations were connected to the data logger. Prior to casting the central portion of the wall (cast 3), the concrete-infilled SHS was positioned in series with a load cell and actuator and grouted into position between the ends of the wall. Just before cast 3, at approximately 4pm, the strut was given a small preload of about 5 kN and left on load-maintain overnight. This ensured that after casting, the strut remained in position and in positive contact with the wall ends as the wall heated up and bent upwards with the ends moving away from each other.

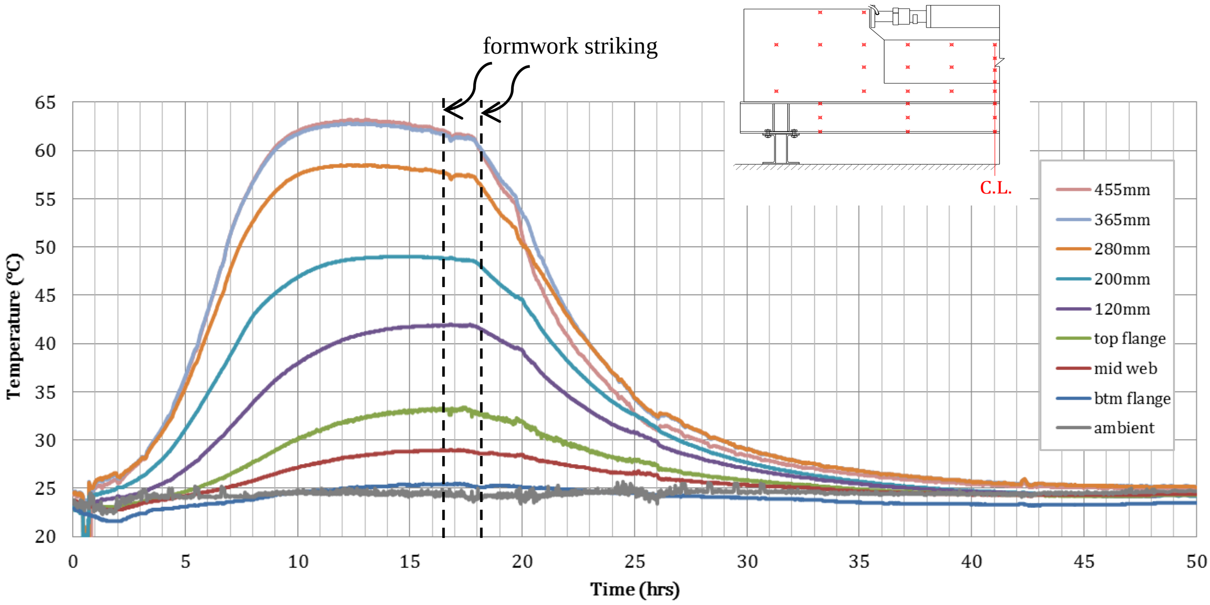
Approximately 18 hours after cast 3, the actuator was removed from load-maintain and locked off leaving a residual preload of approximately 5 kN. The formwork and insulation were then removed from the top and one face of the wall and DEMEC studs were installed on a 150 mm square grid. Subsequently, formwork and insulation were removed from the second wall face and demountable mechanical (DEMEC) studs were attached to it. This order of striking formwork was adopted to minimise cooling of the wall prior to the installation of DEMEC studs.

Concrete compressive and tensile strength tests were carried out at 1, 2, 3, 7, 14 and 28 days. Match-curing was used to assess the influence of high concrete temperatures on concrete maturing. In addition, 250 x 100 mm cylinders were loaded at different ages to determine the concrete elastic modulus and Poisson’s ratio. Two unrestrained walls were also cast to assess the free shrinkage and coefficient of thermal expansion. At the end of the monitoring period, each wall was loaded in flexure under four point bending to investigate the effect of short-term loading on prior cracking due to restraint.

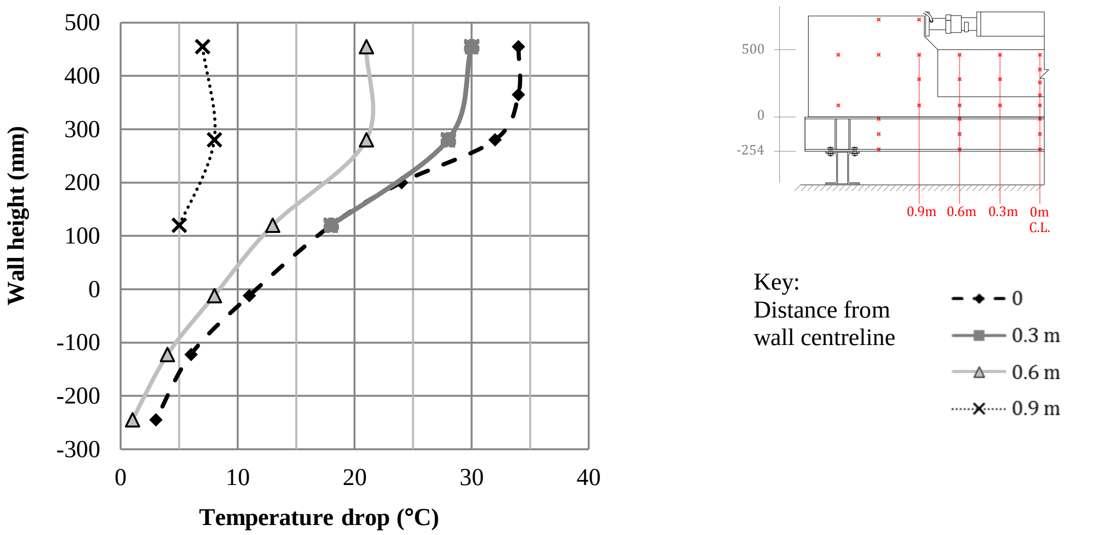
Detailed monitoring was carried out of concrete temperatures, strains, displacements, crack widths, crack spacings, and the strut compressive force. Walls were monitored for a minimum of 6 weeks. Temperatures were monitored with type K thermocouples placed in the wall on a regular grid as well as being attached to the restraining UC. Surface strains were measured between a 150 mm grid of DEMEC points every hour in the first day, daily in the first week and weekly subsequently. Strains were measured over the depth of the restraining beam at three different heights and at five sections along the length. Additionally, end (horizontal) and vertical wall displacements were measured with linear variable differential transformers (LVDTs). Crack propagation was recorded photographically. Crack widths were also measured using a portable crack width microscope with x40 magnification power.

4. Experimental results

This paper presents results for wall C-W8 which are representative. Fig. 5a shows the temperatures recorded at the wall centreline over a period of two days from casting. Temperature drop profiles along the UC and wall height (measured from the top UC flange) at different cross-sections are shown in Fig. 5b. Temperature drops are measured from when formwork was struck until the concrete cooled completely (at about 50 hours from casting).



(a) Temperature variation at different wall heights measured at the wall centreline and over the first two days from casting



(b) Temperature variation with wall height at different sections

Fig. 5. Temperature profiles for C-W8

Fig. 6 shows the crack propagation pattern at the end of the monitoring process. The crack reference system adopted includes a number which indicates the wall age in weeks at the time the crack first formed; week 1 being the first week (i.e. from time of casting till 7 days from casting). The reference number is followed by a letter (a to z), which distinguishes the sequence of crack formation in each week.

In all walls, the first cracks to form were cracks along the cold joints and these occurred on the first day. These cracks are referred to as cracks forming at joints or “j”. Further cracks occurred in the central part of the wall in the second week and in subsequent weeks. These cracks are referred to as internal cracks or “i”. In C-W8, which had the lowest reinforcement amounts, such internal cracks formed later in the first week.

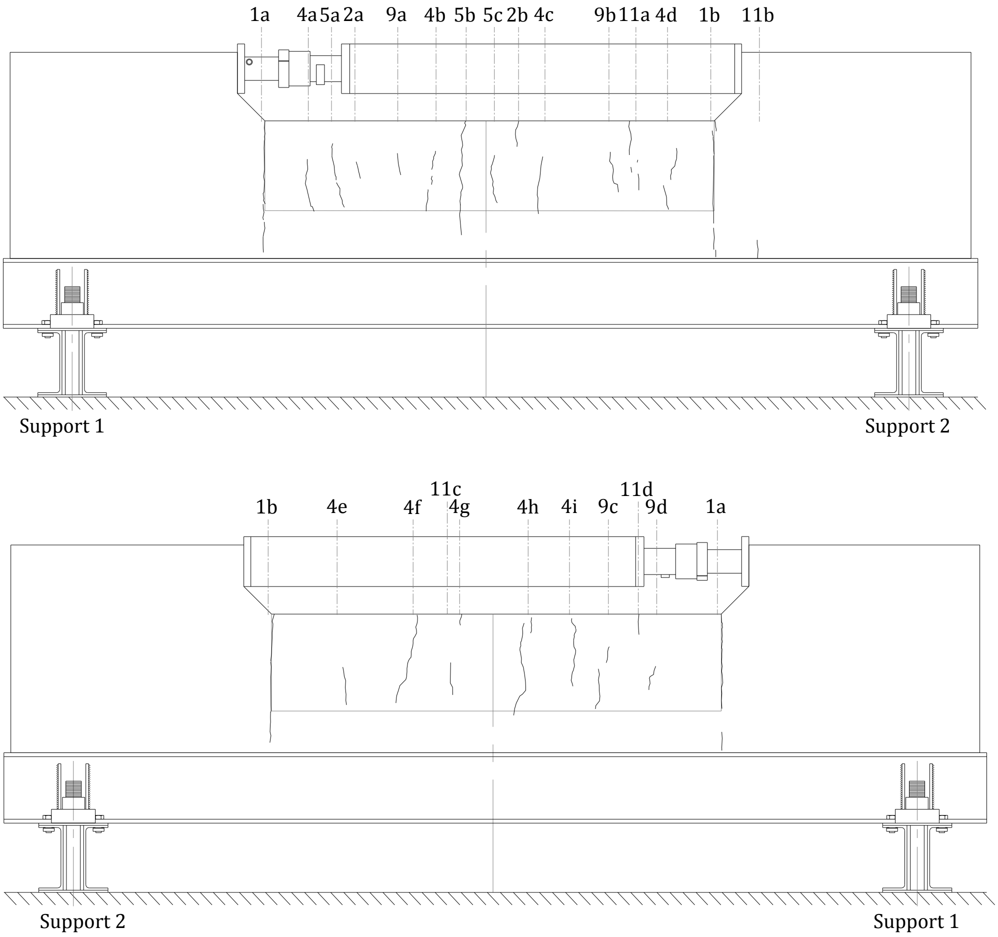


Fig. 6. Crack propagation sequence pattern for both wall faces of C-W8

5. Discussion

Only four specimens were tested and tests were not repeated. Consequently, only limited conclusions can be drawn. Nevertheless, trends emerge from the test results which are discussed in this section.

The vertical cracks at the cold joints appeared first and in the first day. These cracks were widest at both EA and LT even though the reinforcement was continuous through the central wall. This suggests that cold joints between the new and old concrete are the weakest part of the structure, and potentially the locations of widest cracks.

Table 2 summarises the maximum crack widths measured in wall C-W8 at joints (j) and between joints (i) using the crack width microscope at EA (3 days) and at 6 weeks. These are compared with EN 1992 predictions using end restraint prediction equation (3) as well as edge restraint prediction equation (5).

The difference between the EN 1992 and CIRIA Report C660 (Bamforth, 2011) predictions tabulated in Table 2, is in the adopted k_1 in (2). CIRIA Report C660 increases the bond coefficient in (2) from its recommended value of 0.8 in EN1992-1 to 1.14 for EAT cracking. This has the effect of increasing the calculated crack spacing and width and is done to prevent EN1992 from giving significantly smaller reinforcement areas than the superseded U.K. code of practice, BS 8007 (BSI, 1987).

Table 2 clearly shows that the EN 1992 end restraint crack width equation (3) does not give sensible predictions for wall C-W8, with the measured crack widths being overestimated by more than 160 %. On the other hand, much better estimates of crack width are obtained with the EN 1992 and CIRIA Report C660 crack width equations (5) for edge restrained members. These findings were repeated for the other walls with combined edge and end restraint. Results for wall C-W8 are typical.

Table 2. Comparison between values of calculated and observed crack widths

Wall properties (C-W8)	Horizontal bar diameter Ø (mm)		12
	Number of horizontal bars per face		3
	Wall height including kicker (mm)		500
	Horizontal steel area per face A_s (mm^2)		339
	Concrete area A_c (mm^2)		45000
	Reinforcement ratio $\rho = {A_s}/{A_c}$		0.75 %
	${\emptyset}/{\rho}$ (mm)		1592
	Cover c (mm)		45
	Concrete strength f_{ck} (MPa)		40
	Maximum temperature drop T_1 (°C)		34
	EAT maximum restraint		0.53
	LT maximum restraint		0.63
	EA crack-inducing strain ε_{cr} (με)		181
	LT crack-inducing strain ε_{cr} (με)		383
	Coefficient of thermal expansion α (με/°C)		12
Crack widths (mm)	Predicted: EN 1992; end restraint (3)		0.80
	Predicted: CIRIA C660; end restraint (3)		1.10
	Predicted: EN 1992; Edge restraint (5)	EA 3 days	0.13
		LT 6 weeks	0.27
	Predicted: CIRIA C660; edge restraint (5)	EA 3 days	0.17
		LT 6 weeks	0.35
	Measured	EA 3 days (j)	0.20
		LT 6 weeks (j)	0.30
		LT 6 weeks (i)	0.14

6. Conclusions

The present paper reports an overview of an experimental research programme on EAT and LT shrinkage crack control in walls with a combination of edge and end restraint. Results suggest that in the case of walls with combined edge and end restraint, it is more reasonable to adopt the code prediction equation for edge restrained walls rather than for the end restraint scenario. However, the influence of wall aspect ratio requires further consideration.

7. Acknowledgements

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